ENGLISH TRANSLATION OF INTERNATIONAL APPLICATION AS ORIGINALLY FILED

DESCRIPTION

BOUNDARY ACOUSTIC WAVE DEVICE

Technical Field

The present invention relates to a boundary acoustic wave device using a boundary acoustic wave, and more particularly, relates to a boundary acoustic wave device having the structure in which electrodes are disposed at a boundary between a single crystal substrate and a solid layer.

Background Art

Heretofore, various surface acoustic wave devices have been used for RF and IF filters in mobile phones, resonators in VCOs, VIF filters in televisions, and the like. Surface acoustic wave devices use a surface acoustic wave, such as a Rayleigh wave or a first leaky wave, which propagates along a surface of a medium.

However, since propagating along a surface of a medium, a surface acoustic wave is sensitive to the change in surface condition of the medium. Accordingly, in order to protect a surface of a medium along which a surface acoustic wave propagates, a surface acoustic wave element has been hermetic-sealed in a package in which a cavity portion is provided so as to face the wave-propagating surface. Since the package having a cavity portion as described above has been used, the cost of a

surface acoustic wave device is inevitably increased. In addition, since the size of the package becomes much larger than that of a surface acoustic wave element, the size of a surface acoustic wave device is inevitably increased.

On the other hand, among acoustic waves, in addition to the above surface acoustic waves, a boundary acoustic wave is present which propagates along a boundary between solid substances.

For example, in the following Non-Patent Document 1, it has been disclosed that an IDT is formed on a 126° rotated Y plate X-propagation $LiTaO_3$ substrate and that a SiO_2 film having a predetermined thickness is formed on the $LiTaO_3$ substrate and the IDT. In this document, it has been disclosed that an SV+P type boundary acoustic wave, which is a so-called Stoneley wave, propagates. In Non-Patent Document 1, it has been disclosed that when the thickness of the above SiO_2 film is set to 1.0 λ (λ indicates the wavelength of a boundary acoustic wave), an electromechanical coefficient of 2% is obtained.

The boundary acoustic wave propagates in the state in which energy is concentrated at a boundary portion between solid substrates. Hence, since energy is not substantially present on the bottom surface of the above $LiTaO_3$ substrate and the surface of the SiO_2 film, the properties are not changed due to the change in surface conditions of the substrate and the thin film. Accordingly, a package having a cavity portion is not required, and hence the size of the boundary acoustic wave device can be

reduced.

In addition, in the following Non-Patent Document 2, an SH type boundary acoustic wave has been disclosed which propagates in a [001]-Si(110)/SiO_2/Y-cut X-propagation $LiNbO_3$ structure. This SH type boundary acoustic wave is characterized in that an electromechanical coefficient k^2 is large as compared to that of the above Stoneley wave. In addition, in the case of the SH type boundary acoustic wave, a package having a cavity portion is not required as is the case of the Stoneley wave. Furthermore, since the SH type boundary acoustic wave is an SH type wave, it is expected that the reflection coefficient of strips forming an IDT reflector is large as compared to that in the case of the Stoneley wave. Hence, for example, when a resonator or a resonator type filter is formed, miniaturization can be achieved by using the SH type boundary acoustic wave, and in addition, it is also expected that steeper properties can be obtained.

Non-Patent Document 1: "Piezoelectric Acoustic Boundary Waves Propagating Along the Interface Between SiO_2 and $LiTaO_3$" IEEE Trans. Sonics and ultrason., VOL. SU-25, No. 6, 1978 IEEE

Non-Patent Document 2: "Highly Piezoelectric Boundary Acoustic Wave Propagating in Si/SiO_2/$LiNbO_3$ Structure" (26th EM symposium, May 1997, pp. 53 to 58)

Non-Patent Document 3: "Investigation of Piezoelectric SH Type Boundary Acoustic Wave" Technical Report, Vol. 96, No. 249 (US96 45 to 53) PAGE. 21-26, 1966 published by The Institute of

Electronics, Information and Communication Engineers

Patent Document 1: Japanese Unexamined Patent Application Publication No. 10-84247

Disclosure of Invention

In a boundary acoustic wave device, a large electromechanical coefficient, a small propagation loss, a small power flow angle, and a small temperature coefficient of frequency have been required. The loss caused by the propagation of a boundary acoustic wave, that is, the propagation loss, may degrade the insertion loss of a boundary acoustic wave filter or may also degrade the resonant resistance or the impedance ratio of a boundary acoustic wave resonator, the impedance ratio being a ratio between the impedance at a resonant frequency and that at an antiresonant frequency. Hence, the propagation loss is preferably decreased as small as possible.

The power flow angle is an angle indicating the difference between the direction of the phase velocity of a boundary acoustic wave and the direction of the group velocity of energy thereof. When the power flow angle is large, it is necessary to obliquely dispose an IDT in conformity with the power flow angle. Hence, electrode designing becomes complicated. In addition, the loss caused by the deviation in angle is liable to be generated.

Furthermore, when an operating frequency of a boundary

acoustic wave device is changed by the temperature, practical pass band and stop band are decreased in the case of a boundary acoustic wave filter. In the case of a resonator, when an oscillation circuit is formed, the above change in operating frequency caused by the temperature results in abnormal oscillation. Hence, the change in frequency per degree centigrade, which is TCF, is preferably decreased as small as possible.

For example, when reflectors are disposed along a propagation direction and outside a region in which a transmitting IDT and a receiving IDT are provided, which transmits and receives a boundary acoustic wave, respectively, a low-loss resonator type filter can be formed. The band width of this resonator type filter depends on the electromechanical coefficient of a boundary acoustic wave. When the electromechanical coefficient k^2 is large, a broadband filter can be obtained, and when the electromechanical coefficient k^2 is small, a narrowband filter is formed. Hence, it is necessary that the electromechanical coefficient k^2 of a boundary acoustic wave used for a boundary acoustic wave device be appropriately determined in accordance with its application. When an RF filter for mobile phones is formed, the electromechanical coefficient k^2 is required to be 5% or more.

However, in the boundary acoustic wave device using a Stoneley wave, disclosed in the above Non-Patent Document 1, the electromechanical coefficient k^2 was small, such as 2%.

In addition, in the $Si/SiO_2/LiNbO_3$ structure disclosed in the above Non-Patent Document 2, in order to actually excite a boundary acoustic wave, a complicated four-layered structure of $Si/SiO_2/IDT/LiNbO_3$ had to be formed as shown in Fig. 1 of the above Patent Document 1. Furthermore, when Si was actually disposed in the [001]-Si(110) direction proposed as the optimum condition, a bonding process with a high degree of difficulty had to be performed as disclosed in the above Patent Document 1. In general, in the case of a wafer having a diameter of 3 inches or more, which is used for mass production, it has been difficult to uniformly bond wafers together by a bonding process. In addition, after the wafer bonding is carried out, when cutting is performed to form chips, inconveniences such as peeling are liable to occur.

As for the SH type boundary acoustic wave, as described in the above Non-Patent Document 3, in the structure made of an isotropic substance and a BGSW substrate, when the following conditions are satisfied, that is, the acoustic velocity of a transverse wave of the isotropic substance and that of the BGSW substrate are close to each other, the density ratio is small, and piezoelectric properties are strong, the SH type boundary acoustic wave can be obtained.

In consideration of the current status of the above-described conventional techniques, an object of the present invention is to provide a boundary acoustic wave device in which the electromechanical coefficient, which is a main response of

an SH boundary acoustic wave, is large, the transmission loss and the power flow angle are small, and a spurious signal caused by a Stoneley wave in the vicinity of the main response is small.

Another object of the present invention is to provide a boundary acoustic wave device in which the electromechanical coefficient, which is the main response of an SH type boundary acoustic wave, can be easily adjusted.

In accordance with the present invention, there is provided a boundary acoustic wave device using a non-leaky propagation type boundary acoustic wave, comprising boundary acoustic wave elements which are formed using a single crystal substrate having the same cut angle. In the boundary acoustic wave device described above, the boundary acoustic wave elements each include the single crystal substrate, a solid layer provided thereon, and electrodes proved at a boundary between the single crystal substrate and the solid layer, and of the boundary acoustic wave elements, the propagation direction of a boundary acoustic wave of at least one of the boundary acoustic wave elements is different from that of at least one of the other boundary acoustic wave elements.

In the present invention, although not being particularly limited, for example, the boundary acoustic wave elements may be boundary acoustic wave filters or boundary acoustic wave resonators.

In the boundary acoustic wave device according to the

present invention, the boundary acoustic wave elements preferably have a resonator structure.

In accordance with a specific aspect of the boundary acoustic wave device of the present invention, there is provided a longitudinally coupled filter as the boundary acoustic wave device.

In accordance with another specific aspect of the boundary acoustic wave device of the present invention, the boundary acoustic wave elements are formed on one piezoelectric single crystal substrate.

In accordance with another specific aspect of the boundary acoustic wave device of the present invention, the electromechanical coefficient of at least one of the boundary acoustic wave elements is different from that of at least one of the other boundary acoustic wave elements.

In accordance with another specific aspect of the boundary acoustic wave device of the present invention, the band width of at least one of the boundary acoustic wave elements is different from that of at least one of the other boundary acoustic wave elements.

In accordance with another specific aspect of the boundary acoustic wave device of the present invention, the thickness of the electrodes is set so that the acoustic velocity of the SH type boundary acoustic wave is lower than the acoustic velocity of a slow transverse wave propagating through the solid layer and the acoustic velocity of a slow transverse wave propagating

through the piezoelectric single crystal substrate.

In accordance with another specific aspect of the boundary acoustic wave device of the present invention, the duty ratio of the electrodes is set so that the acoustic velocity of the SH type boundary acoustic wave is lower than the acoustic velocity of a slow transverse wave propagating through the solid layer and the acoustic velocity of a slow transverse wave propagating through the piezoelectric single crystal substrate.

In the present invention, when the density of the electrodes, the thickness of the electrodes, and the wavelength of a boundary acoustic wave are represented by ρ (kg/m^3), H (λ), and λ, respectively, it is preferable that $H>8261.744\rho^{-1.376}$ be satisfied. In addition, it is more preferable that $\rho>3,745$ kg/m^3 be satisfied. Furthermore, it is even more preferable that $33,000.39050\rho^{-1.50232}<H<88,818.90913\rho^{-1.54998}$ be satisfied.

In accordance with another specific aspect of the boundary acoustic wave device of the present invention, the piezoelectric single crystal substrate is a $LiNbO_3$ substrate, ϕ of Euler angles (ϕ, θ, ψ) of the $LiNbO_3$ substrate is in the range of -31° to 31°, and θ and ψ are in the range surrounded by points A1 to A13 shown in the following Table 1.

[Table 1]

Points	ψ (°)	θ (°)
A01	0	116
A02	11	118
A03	20	123
A04	25	127
A05	33	140
A06	60	140
A07	65	132
A08	54	112
A09	48	90
A10	43	87
A11	24	90
A12	0	91
A13	0	116

In accordance with another specific aspect of the boundary acoustic wave device of the present invention, the electrodes each comprise a main electrode layer formed of one material selected from the group consisting of Au, Ag, Cu, Al, Fe, Ni, W, Ta, Pt, Mo, Cr, Ti, ZnO, and ITO.

In accordance with another specific aspect of the boundary acoustic wave device of the present invention, the electrodes each further comprise a second electrode layer laminated on the main electrode layer.

In accordance with another specific aspect of the boundary acoustic wave device of the present invention, the solid layer comprises a dielectric substance. Preferably, the solid layer is formed of a material primarily composed of SiO_2.

In accordance with another specific aspect of the boundary acoustic wave device of the present invention, the solid layer is formed of a plurality of laminates which are each formed by

laminating a plurality of material layers.

In addition, in accordance with another specific aspect of the boundary acoustic wave device of the present invention, the solid layer has the structure in which a layer primarily composed of SiO_2 and a layer primarily composed of Si are laminated to each other.

In accordance with another specific aspect of the boundary acoustic wave device of the present invention, the solid layer is formed of at least one material selected from the group consisting of Si, SiO_2, glass, silicon nitride, silicon carbide, ZnO, Ta_2O_5, titanate zirconate lead piezoelectric ceramic, aluminum nitride, Al_2O_3, $LiTaO_3$, and $LiNbO_3$.

In accordance with another specific aspect of the boundary acoustic wave device of the present invention, a resin layer is further provided on the solid layer so as to be adhered thereto.

In the boundary acoustic wave device according to the present invention, boundary acoustic wave elements are formed using a single crystal substrate having the same cut angle, the boundary acoustic wave elements each include the single crystal substrate, a solid layer, and electrodes provided at a boundary between the single crystal substrate and the solid layer, and of the boundary acoustic wave elements, the propagation direction of a boundary acoustic wave of at least one of the boundary acoustic wave elements is different from that of at least one of the other boundary acoustic wave elements. Accordingly, a boundary acoustic wave device having various band

characteristics, such as broadband filter characteristics and narrowband filter characteristics, can be easily provided by using a plurality of boundary acoustic wave elements which have different propagation directions of a boundary acoustic wave.

In addition, in a leaky propagation type surface acoustic wave device represented by a 36° Y-cut X-propagation $LiTaO_3$ substrate, for example, the propagation loss becomes approximately zero only when the surface acoustic wave propagates at a specific propagation angle such as 0° direction with respect to the crystal axis X, and when the propagation angle is shifted from the above value, the propagation loss is disadvantageously increased.

On the other hand, since the non-leaky propagation type boundary acoustic wave is used in the present invention, even when the propagation angle is changed, the propagation loss can be made 0 dB/λ, and as a result, a boundary acoustic wave device having a low loss can be provided.

When the above boundary acoustic wave device is a boundary acoustic wave filter or a boundary acoustic wave resonator, in accordance with the present invention, a boundary acoustic wave filter and a boundary acoustic wave resonator, having various band characteristics, can be provided.

In the present invention, by changing the propagation direction of a boundary acoustic wave, for example, the electromechanical coefficient can be adjusted, and as a result, the insertion loss can be varied in the case of a transversal

filter having no resonance structure. Furthermore, in a boundary acoustic wave resonator, a ladder filter, a longitudinally coupled multimode type boundary acoustic wave filter and the like, which have a resonance structure, the frequency interval between the resonant frequency and antiresonant frequency can be adjusted in proportion to the electromechanical coefficient in the case of the resonator, and in the case of the ladder filter or longitudinally coupled multimode type boundary acoustic wave filter, which exploits the resonator, the pass band can be adjusted in proportion to the electromechanical coefficient.

In the present invention, when the boundary acoustic wave elements are formed on one piezoelectric single crystal substrate, in accordance with the present invention, a boundary acoustic wave device having various band characteristics can be formed as a chip component.

In the present invention, when the electromechanical coefficient of at least one boundary acoustic wave element is different from that of at least one of the other boundary acoustic wave elements, various band widths can be easily realized by changing the electromechanical coefficients of the boundary acoustic wave elements.

When the band width of at least one boundary acoustic wave element is different from that of at least one of the other boundary acoustic wave elements, various band characteristics can be obtained by combination of band widths.

In the present invention, when the thickness of the electrodes is set so that the acoustic velocity of an SH type boundary acoustic wave is lower than the acoustic velocity of a slow transverse wave propagating through the solid layer and the acoustic velocity of a slow transverse wave propagating through the piezoelectric single crystal substrate, in accordance with the present invention, a boundary acoustic wave device using an SH type boundary acoustic wave can be provided.

When the duty ratio of the electrodes is set so that the acoustic velocity of an SH type boundary acoustic wave is lower than the acoustic velocity of a slow transverse wave propagating through the solid layer and the acoustic velocity of a slow transverse wave propagating through the piezoelectric single crystal substrate, in accordance with the present invention, a boundary acoustic wave device using an SH type boundary acoustic wave can be reliably provided.

Brief Description of the Drawings

Figs. 1(a) and 1(b) are a plan view showing a boundary acoustic wave device of one embodiment according to the present invention and a cross-sectional view taken along an A-A line shown in Fig. 1(a), respectively.

Fig. 2 is a graph showing the relationship between an acoustic velocity V and an electrode thickness H/λ, which is obtained when electrodes are formed between a piezoelectric substance and a dielectric substance by using electrode

materials having different densities.

Fig. 3 is a graph showing the relationship between a propagation loss α and an electrode thickness H/λ, which is obtained when electrodes are formed between a piezoelectric substance and a dielectric substance by using electrode materials having different densities.

Fig. 4 is a graph showing the relationship between an electromechanical coefficient k^2 and an electrode thickness H/λ, which is obtained when electrodes are formed between a piezoelectric substance and a dielectric substance by using electrode materials having different densities.

Fig. 5 is a graph showing the relationship between a temperature coefficient of frequency TCF and an electrode thickness H/λ, which is obtained when electrodes are formed between a piezoelectric substance and a dielectric substance by using electrode materials having different densities.

Fig. 6 is a graph showing the relationship between a power flow angle PFA and an electrode thickness H/λ, which is obtained when electrodes are formed between a piezoelectric substance and a dielectric substance by using electrode materials having different densities.

Fig. 7 is a graph showing the relationship between a density ρ of an electrode material and an electrode thickness H/λ at which a propagation loss of 0 is obtained.

Fig. 8 is a graph showing the relationship between a density ρ of an electrode material and an electrode thickness H/λ

at which TCFs of -20, -10, 0, +10, and +20 are obtained.

Fig. 9 is a graph showing the relationships of θ of the Euler angles with an acoustic velocity V of an SH type boundary acoustic wave (U2) and that of a Stoneley wave (U3), which are obtained in the structure in which Au electrodes are formed on a $LiNbO_3$ substrate with Euler angles (0°, θ, 0°) and in which a SiO_2 film is formed.

Fig. 10 is a graph showing the relationships of θ of the Euler angles with an electromechanical coefficient k^2 of an SH type boundary acoustic wave (U2) and that of a Stoneley wave (U3), which are obtained in the structure in which Au electrodes are formed on a $LiNbO_3$ substrate with Euler angles (0°, θ, 0°) and in which a SiO_2 film is formed.

Fig. 11 is a graph showing the relationships of θ of the Euler angles with a temperature coefficient of frequency of an SH type boundary acoustic wave (U2) and that of a Stoneley wave (U3), which are obtained in the structure in which Au electrodes are formed on a $LiNbO_3$ substrate with Euler angles (0°, θ, 0°) and in which a SiO_2 film is formed.

Fig. 12 is a graph showing the relationship between θ and ψ of the Euler angles and an electromechanical coefficient k^2 of an SH type boundary acoustic wave, which is obtained in Experimental Example 2 in which Au electrodes having a thickness of 0.06 λ are formed on a $LiNbO_3$ substrate with Euler angles (0°, θ, ψ), followed by formation of a SiO_2 film.

Fig. 13 is a graph showing the relationship between θ and ψ

of the Euler angles and an electromechanical coefficient k^2 of a Stoneley wave, which is obtained in Experimental Example 2 in which Au electrodes having a thickness of 0.06 λ are formed on a $LiNbO_3$ substrate with Euler angles (0°, θ, ψ), followed by formation of a SiO_2 film.

Fig. 14 is a graph showing the relationships of ϕ of the Euler angles with an acoustic velocity V of an SH type boundary acoustic wave and that of a Stoneley wave, which are obtained in Experimental Example 3 in which a $LiNbO_3$ substrate with Euler angles (ϕ, 105°, 0°) is used.

Fig. 15 is a graph showing the relationship between ϕ of the Euler angles and a temperature coefficient of frequency TCF, which is obtained in Experimental Example 3 in which a $LiNbO_3$ substrate with Euler angles (ϕ, 105°, 0°) is used.

Fig. 16 is a graph showing the relationship between ϕ of the Euler angles and an electromechanical coefficient k^2, which is obtained in Experimental Example 3 in which a $LiNbO_3$ substrate with Euler angles (ϕ, 105°, 0°) is used.

Fig. 17 is a graph showing the relationship between ϕ of the Euler angles and a power flow angle, which is obtained in Experimental Example 3 in which a $LiNbO_3$ substrate with Euler angles (ϕ, 105°, 0°) is used.

Fig. 18 is a graph showing the relationships of ϕ of the Euler angles with an acoustic velocity V of an SH type boundary acoustic wave and that of a Stoneley wave, which are obtained in Experimental Example 3 in which a $LiNbO_3$ substrate with Euler

angles (0°, 105°, ψ) is used.

Fig. 19 is a graph showing the relationship between φ of the Euler angles and a temperature coefficient of frequency TCF, which is obtained in Experimental Example 3 in which a $LiNbO_3$ substrate with Euler angles (0°, 105°, ψ) is used.

Fig. 20 is a graph showing the relationship between φ of the Euler angles and an electromechanical coefficient k^2, which is obtained in Experimental Example 3 in which a $LiNbO_3$ substrate with Euler angles (0°, 105°, ψ) is used.

Fig. 21 is a graph showing the relationship between φ of the Euler angles and a power flow angle, which is obtained in Experimental Example 3 in which a $LiNbO_3$ substrate with Euler angles (0°, 105°, ψ) is used.

Fig. 22 is a schematic plan view for illustrating an electrode structure of a boundary acoustic wave resonator prepared in Experimental Example 5.

Figs. 23(a) to 23(c) are graphs showing impedance-frequency characteristics and phase-frequency characteristics, which are obtained when the propagation directions are inclined so that ψ of the Euler angles of a crystal substrate of a one-port type boundary acoustic wave resonator prepared in Experimental Example 5 is set to 0°, 10°, and 20°.

Figs. 24(a) to 24(c) are graphs showing impedance-frequency characteristics and phase-frequency characteristics, which are obtained when the propagation directions are inclined so that ψ of the Euler angles of a crystal substrate of the one-port type

boundary acoustic wave resonator prepared in Experimental Example 5 is set to 30°, 40°, and 50°.

Figs. 25(a) to 25(c) are graphs showing the relationships of ψ of the Euler angles with the difference between the resonant and antiresonant frequencies, which are obtained when the thickness H/λ of electrodes which are made of Au and which are provided on a $LiNbO_3$ substrate with Euler angles (0°, 95°, ψ) is set to 0.04, 0.05 and 0.06.

Figs. 26(a) to 26(c) are graphs showing the relationships of ψ of the Euler angles with the difference between the resonant and antiresonant frequencies, which are obtained when the thickness H/λ of electrodes which are made of Au and which are provided on a $LiNbO_3$ substrate with Euler angles (0°, 100°, ψ) is set to 0.04, 0.05 and 0.06.

Figs. 27(a) to 27(c) are graphs showing the relationships of ψ of the Euler angles with the difference between the resonant and antiresonant frequencies, which are obtained when the thickness H/λ of electrodes which are made of Au and which are provided on a $LiNbO_3$ substrate with Euler angles (0°, 105°, ψ) is set to 0.04, 0.05 and 0.06.

Figs. 28(a) to 28(c) are graphs showing the relationships of ψ of the Euler angles with the difference between the resonant and antiresonant frequencies, which are obtained when the thickness H/λ of electrodes which are made of Au and which are provided on a $LiNbO_3$ substrate with Euler angles (0°, 110°, ψ) is set to 0.04, 0.05 and 0.06.

Figs. 29(a) to 29(c) are graphs showing the relationships between ψ of the Euler angles and the impedance, which are obtained when the thickness H/λ of electrodes which are made of Au and which are provided on a $LiNbO_3$ substrate with Euler angles (0°, 95°, ψ) is set to 0.04, 0.05 and 0.06.

Figs. 30(a) to 30(c) are graphs showing the relationships between ψ of the Euler angles and the impedance, which are obtained when the thickness H/λ of electrodes which are made of Au and which are provided on a $LiNbO_3$ substrate with Euler angles (0°, 100°, ψ) is set to 0.04, 0.05 and 0.06.

Figs. 31(a) to 31(c) are graphs showing the relationships between ψ of the Euler angles and the impedance, which are obtained when the thickness H/λ of electrodes which are made of Au and which are provided on a $LiNbO_3$ substrate with Euler angles (0°, 105°, ψ) is set to 0.04, 0.05 and 0.06.

Figs. 32(a) to 32(c) are graphs showing the relationships between ψ of the Euler angles and the impedance, which are obtained when the thickness H/λ of electrodes which are made of Au and which are provided on a $LiNbO_3$ substrate with Euler angles (0°, 110°, ψ) is set to 0.04, 0.05 and 0.06.

Fig. 33 is a view showing a circuit diagram of a ladder filter prepared in Experimental Example 5.

Figs. 34(a) and 34(b) are graphs each showing pass characteristics obtained when ψ of the Euler angles of a ladder filter prepared in Experimental Example 6 is set to 0° and 10°.

Figs. 35(a) and 35(b) are graphs each showing pass

characteristics obtained when ψ of the Euler angles of a ladder filter prepared in Experimental Example 6 is set to 20° and 30°.

Fig. 36 is a graph showing pass characteristics of a ladder filter prepared in Experimental Example 8.

Fig. 37 is a graph showing pass characteristics of a ladder filter prepared in Experimental Example 6 in which an electrode material is changed to Cu.

Figs. 38(a) to 38(c) are graphs showing the relationships of θ of the Euler angles with an acoustic velocity V, an electromechanical coefficient k^2, and a temperature coefficient of frequency in the structure in which Au electrodes are formed on a $LiNbO_3$ substrate of (0°, θ, 0°) and in which a polycrystalline Si layer is formed.

Figs. 39(a) to 39(c) are graphs showing the relationships of θ of the Euler angles with an acoustic velocity V, an electromechanical coefficient k^2, and a temperature coefficient of frequency in the structure in which Au electrodes are formed on a $LiNbO_3$ substrate of (0°, θ, 0°) and in which a SiO_2 film and polycrystalline Si are formed.

Fig. 40 is a schematic view of another example of a filter prepared in Experimental Example 8 to which the present invention is applied.

Fig. 41 is a graph showing frequency characteristics of an Rx filter and a Tx filter of the filter shown in Fig. 40.

Fig. 42 is a block diagram for illustrating another example to which the present invention is applied.

Fig. 43 is a circuit diagram for illustrating another example of a filter to which the present invention is applied.

Fig. 44 is a graph for illustrating frequency characteristics of the filter shown in Fig. 43.

Fig. 45 is a circuit diagram for illustrating another example of a filter to which the present invention is applied.

Fig. 46 is a plan view schematically showing an electrode structure of a longitudinally coupled filter formed in accordance with the present invention.

Fig. 47 is a graph showing one example of filter characteristics of the longitudinally coupled filter shown in Fig. 46.

Fig. 48 is a graph showing another example of filter characteristics of the longitudinally coupled filter shown in Fig. 46.

Reference Numerals

1 boundary acoustic wave device

2 boundary acoustic wave element

3 boundary acoustic wave element

4 single crystal substrate

5 solid layer

6 IDT

7, 8 reflector

9 IDT

10, 11 reflector

31 interdigital electrode

32, 33 reflector

41, 43 Rx filter

42, 44 Tx filter

45, 47 first boundary acoustic wave filter

46, 48 second boundary acoustic wave filter

51 longitudinally coupled filter

52 to 54 IDT

55, 56 reflector

Best Mode for Carrying Out the Invention

Hereinafter, particular embodiments of the present invention will be described so as to clearly disclose the present invention.

In order to propagate a boundary acoustic wave between two solid layers, the condition in that energy of the boundary acoustic wave is concentrated between the solid layers must be satisfied. In the above case, as described above, a method has been disclosed in the above Non-Patent Document 3 in which the transverse acoustic velocity of the isotropic substance is made close to that of the BGSW substrate, the density ratio is set to small, and a material having strong piezoelectric properties is selected.

Incidentally, in general, when a high velocity region and a low velocity region are present, the wave is concentrated on a part at which the acoustic velocity is low and is propagated.

The inventor of the present invention found that the condition in that energy is concentrated between solid layers can be satisfied when the acoustic velocity of a boundary acoustic wave propagating between the solid layers is decreased by increasing the thickness of electrodes using a metal material, such as Au, which has a high density and a low acoustic velocity as an electrode material provided between the solid layers, and as a result, the present invention was made.

Heretofore, it has been known that as bulk waves propagating in a solid substance, three types of waves, that is, a longitudinal wave, a fast transverse wave, and a slow transverse wave are present, and that they are called a P wave, an SH wave, and a SV wave, respectively. Whether the SH wave or the SV wave becomes a slow transverse wave is determined by the anisotropic properties of a base material. Among the above three types of bulk waves, a bulk wave having the lowest acoustic velocity is a slow transverse wave. When the solid substance is an isotropic substance such as SiO_2, since only one type of transverse wave propagates therethrough, this transverse wave is a slow transverse wave.

On the other hand, in a boundary acoustic wave propagating through an anisotropic base material such as a piezoelectric substrate, in most cases, three displacement components of the P wave, SH wave, and SV wave propagate while being coupled with each other, and by the primary component, the type of boundary acoustic wave is determined. For example, the above Stoneley

wave is a boundary acoustic wave primarily composed of the P wave and the SV wave, and the SH type boundary acoustic wave is a boundary acoustic wave primarily composed of the SH component. In addition, depending on the conditions, the SH wave component and the P wave or the SV wave component may propagate in some cases without being coupled with each other.

In the boundary acoustic wave, since the above three displacement components propagate while being coupled with each other, for example, in a boundary acoustic wave having an acoustic velocity faster than that of the SH wave, the SH component and the SV component leak, and in a boundary acoustic wave having an acoustic velocity faster than that of the SV wave, the SV component leaks. This leaky-wave component causes the propagation loss of the boundary acoustic wave.

Accordingly, when the acoustic velocity of the SH type boundary acoustic wave is decreased lower than the acoustic velocities of slow transverse waves of the above two solid layers, energy of the SH type boundary acoustic wave can be concentrated around electrodes disposed between the two solid layers, and as a result, the conditions can be obtained in which the propagation loss is zero. In addition, when at least one of the solid layers is formed from a piezoelectric substance, and a dielectric substance containing a piezoelectric substance is used as the other solid layer, by the electrodes disposed between the solid layers, the SH type boundary acoustic wave can be excited. The electrodes may include comb electrodes or

interdigital electrodes as disclosed, for example, by Mikio SHIBAYAMA in "Surface Acoustic Wave Technology" pp. 57 to 58, published by The Institute of Electronics, Information and Communication Engineers. The above structure is a simple structure in which electrodes are disposed between two solid layers. In addition, by the above structure, the SH type boundary acoustic wave can be used by combination of very many materials. For example, in a SiO_2/IDT electrode/Y-X $LiNbO_3$ structure, although excitation of the SH type boundary acoustic wave has not been confirmed, when the thickness of the electrodes is increased, the SH type boundary acoustic wave is allowed to exist.

In addition, in the case of an IDT and a grating reflector, when the ratio of a strip line width to the placement period of strips forming the IDT and the grating reflector, that is, the duty ratio is increased while the acoustic velocity of a slow transverse wave is made close to that of the boundary acoustic wave by increasing the electrode thickness, the acoustic velocity of the SH type boundary acoustic wave can be decreased lower than that of the slow transverse wave.

Figs. 1(a) and 1(b) are views for illustrating a boundary acoustic wave device of one embodiment according to the present invention. Fig. 1(a) is a schematic plan view showing electrode structures, and Fig. 1(b) is a front cross-sectional view schematically showing a part taken along a line A-A shown in Fig. 1(a).

As shown in Fig. 1(a), in a boundary acoustic wave device 1, in order to form a first boundary acoustic wave element 2 and a second boundary acoustic wave element 3, the electrode structures are formed.

In addition, as shown in Fig. 1(b), in the boundary acoustic wave device 1, a solid layer 5 is formed on an upper surface of a plate-shaped single crystal substrate 4, and the above electrode structures are formed at the boundary between the single crystal substrate 4 and the solid layer 5.

In more particular, the single crystal substrate 4 used in this embodiment is formed of a Y plate X-propagation $LiNbO_3$ substrate with Euler angles (0°, 90°, 0°) which functions as a piezoelectric crystal. In addition, the solid layer 5 is formed of SiO_2 which functions as a dielectric substance. Since being composed of SiO_2, the solid layer 5 can be easily formed by a thin-film forming method. In addition, SiO_2 has a temperature coefficient of frequency TCF for counteracting a temperature coefficient of frequency TCF of $LiNbO_3$. Hence, when the solid layer composed of SiO_2 is used, the temperature characteristics can be improved.

In addition, the electrode structure of the boundary acoustic wave element 2 has interdigital electrodes 6 and reflectors 7 and 8 disposed at two sides of the interdigital electrodes 6 along the propagation direction of a boundary acoustic wave. The interdigital electrodes 6 have a plurality of electrode fingers which interdigitate with each other, and

the grating reflectors 7 and 8 each have a plurality of electrode fingers which are short-circuited at two ends. That is, the boundary acoustic wave element 2 is a one-port type resonator.

The second boundary acoustic wave element 3 is also a one-port type resonator and has interdigital electrodes 9 and reflectors 10 and 11.

The first and the second boundary acoustic wave elements 2 and 3 are each configured by forming the above electrode structure between the piezoelectric crystal substrate 4 and the solid layer 5. That is, in this embodiment, the boundary acoustic wave elements 2 and 3 are formed by using the same piezoelectric crystal substrate 4. In addition, in the present invention, a plurality of boundary acoustic wave elements may be formed by using different piezoelectric crystal substrates.

The electrode structures described above may be formed by using an optional metal material. In this embodiment, the electrode structures are formed from Au.

In addition, the feature of the boundary acoustic wave device 1 of this embodiment is that the propagation direction of the boundary acoustic wave of the first boundary acoustic wave element 2 is different from that of the second boundary acoustic wave element 3. That is, a propagation direction X1 of the boundary acoustic wave of the first boundary acoustic wave element 2 is different from a propagation direction X2 of the boundary acoustic wave of the second boundary acoustic wave

element 3. As shown in Fig. 1(a), the boundary acoustic wave elements 2 and 3 are disposed so that the propagation direction X2 has an angle β with respect to the propagation direction X1. The principle and function of the boundary acoustic wave device 1 of this embodiment will be described in more particular detail with reference to experimental examples.

[Experimental Example 1]

In the case in which electrodes were formed between a solid layer of SiO_2 and a single crystal $LiNbO_3$ substrate with Euler angles (0°, 90°, 0°) by using electrode materials having different densities, the relationships of an electrode thickness H/λ (in which H indicates the thickness, and λ indicates the wavelength of an SH type boundary acoustic wave) with the acoustic velocity, a propagation loss α, an electromechanical coefficient k^2 (%), a temperature coefficient of frequency TCF (ppm/°C), and a power flow angle (PFA) of a boundary acoustic wave are shown in Figs. 2 to 6, respectively.

The results shown in Figs. 2 to 6 were obtained by calculation based on a method disclosed in "A method for estimating optimal cuts and propagation directions for excitation and propagation directions for excitation of piezoelectric surface waves" (J. J. Campbell and W. R. Jones, IEEE Trans. Sonics and Ultrason., Vol. SU-15 (1968) pp. 209 to 217).

In the case of a free boundary, the acoustic velocity and the propagation loss were obtained based on the assumption in

which the displacements, the potentials, the normal line components of an electric flux density, and the stresses in the up and down direction at respective boundaries between SiO_2 and Au and between Au and $LiNbO_3$ were continuous, the thickness of SiO_2 and that of $LiNbO_3$ were infinite, and the relative dielectric constant of Au was 1. In addition, in the case of a short-circuit boundary, the potentials at the respective boundaries between SiO_2 and Au and between Au and $LiNbO_3$ were regarded as zero. In addition, the electromechanical coefficient k^2 was obtained by the following equation (1).

$k^2=2\times|Vf-V|/Vf$ ··· Equation (1)

In the above equation, Vf indicates the acoustic velocity of the free boundary.

The temperature coefficient of frequency TCF was obtained from phase velocities V at 20, 25, and 30°C using the following equation (2).

$TCF=V^{-1}(25°C)\times[(V(30°C)-V(20°C)/10°C)]-\alpha s$ ··· Equation (2)

In the above equation, αs indicates the coefficient of linear thermal expansion of the $LiNbO_3$ substrate in the propagation direction of the boundary acoustic wave.

In addition, the power flow angle PFA at optional Euler angles (ϕ, θ, ψ) was obtained from phase velocities V at angles of ψ-0.5°, ψ, and ψ+0.5° using the following equation (3).

$PFA=\tan^{-1}[V^{-1}(\psi)\times(V(\psi+0.5°)-V(\psi-0.5°)]$ ··· Equation (3)

The acoustic velocities of a longitudinal wave, a fast transverse wave, and a slow transverse wave in the Y plate X-

propagation $LiNbO_3$ are 6,547, 4,752, and 4,031 m/sec, respectively. In addition, the acoustic velocities of a longitudinal wave and a slow transverse wave of SiO_2 are 5,960 and 3,757 m/sec, respectively.

According to Figs. 2 and 3, it is understood that at the thickness at which the acoustic velocity of the SH type boundary acoustic wave is not more than 3,757 m/sec which is the lowest velocity of the above longitudinal wave, fast transverse wave, and slow transverse wave, the propagation loss α of the SH type boundary acoustic wave can be decreased to zero by any type of electrode material.

Fig. 7 is a graph showing the relationship between a density ρ of the electrode material and an electrode thickness H at which the propagation loss of the SH type boundary acoustic wave becomes zero. As apparent from Fig. 7, it is understood that when the condition of the following equation (4) is satisfied, an SH type boundary acoustic wave having a propagation loss α of zero can be obtained.

$H(\lambda) > 8{,}261.744\rho^{-1.376}$ ··· Equation (4)

In addition, when this type of boundary acoustic wave device is manufactured, electrodes such as IDTs are formed on a piezoelectric substrate made of $LiNbO_3$ or the like by a photolithographic technique including lift-off, dry etching, or the like, and on the electrodes, a dielectric film made of SiO_2 or the like is formed by a deposition method, such as sputtering, evaporation, or CVD. Hence, by irregularities

caused by the thickness of the IDT, the dielectric film may be obliquely grown or the film quality may become non-uniform, and as a result, the properties of the boundary acoustic wave device may be degraded in some cases. In order to avoid the degradation of the properties described above, the thickness of the electrodes is preferably decreased as small as possible.

According to investigation carried out by the inventors of the present invention, when the film thickness H of the electrode material for the IDT or the like is 0.1 λ or more, because of the irregularities thereof, formation of a dielectric film having superior quality becomes very difficult, and hence the electrode thickness H is preferably decreased to 0.1 λ or less. Accordingly, from Fig. 7, it is understood that when an electrode material having a density ρ of 3,745 kg/m^3 or more is used, the electrode thickness H can be decreased to 0.1 λ at which the propagation loss becomes zero.

In addition, as apparent from Fig. 4, at the electrode thickness which satisfies the above equation (4), the electromechanical coefficient k^2 is large, such as 10 to 38%, and hence it is understood that a broadband boundary acoustic wave device having a low loss can be provided.

In addition, as apparent from Fig. 5, it is understood that the temperature coefficient of frequency TCF is in the range of -40 to +40 ppm/°C under most conditions and that by adjustment of the electrode thickness, the TCF can be decreased to ±20 ppm/°C or less, to ±10 ppm/°C or less, and further to ±0 ppm/°C

or less.

Fig. 8 is a graph showing points indicating the relationship between the density ρ of the electrode material and the electrode thickness H at which TCFs of -20, -10, 0, -10, and +20 ppm/°C are obtained and also showing an approximation curve made from the above points. As apparent from Fig. 8, an electrode thickness H at which the TCF is in a preferable range of -20 to +20 ppm/°C is in the range which satisfies the following equation (5), an electrode thickness H at which the TCF is in a more preferable range of -10 to +10 ppm/°C is in the range which satisfies the following equation (6), and an electrode thickness H at which the TCF most preferably becomes 0 ppm/°C is obtained when the following equation (7) is satisfied.

$33,000.39050\rho^{-1.50232}<H<88,818.90913\rho^{-1.54998}$ ··· Equation (5)

$49,889.90887\rho^{-1.53872}<H<112,510.78359\rho^{-1.60019}$ ··· Equation (6)

$H=96,984.47020\rho^{-1.59706}$ ··· Equation (7)

In addition, as apparent from Fig. 6, it is understood that the power flow angle PFA is superior, such as 0 at any film thickness H.

[Experimental Example 2]

Based on the results obtained in Experimental Example 1, electrodes of Au having a thickness of 0.05 λ were formed on a $LiNbO_3$ substrate with Euler angles (0°, θ, 0°), and a SiO_2 film was formed so as to cover the electrodes of Au. In this structure, the relationships of θ of the Euler angles of the $LiNbO_3$ substrate with the acoustic velocities V, the

electromechanical coefficients k^2, the propagation losses α, the temperature coefficients of frequency TCF, and the power flow angles (PFA) of an SH type boundary acoustic wave and a Stoneley wave were measured. Figs. 9 to 11 show the relationships of the Euler angle θ with the acoustic velocity, the electromechanical coefficient k^2, and the temperature coefficient of frequency TCF. In the entire region of θ=0° to 180°, the propagation loss α was 0 dB/λ and the power flow angle (PFA) was 0°.

In Figs. 9 to 11, U2 indicates the SH type boundary acoustic wave, and U3 indicates the Stoneley wave which causes a spurious signal.

As apparent from Fig. 10, it is understood that when the Euler angle θ is 106°, the electromechanical coefficient k^2 of the Stoneley wave, which causes a spurious signal, becomes approximately 0%.

Next, electrodes of Au having a thickness of 0.06 λ were formed on a $LiNbO_3$ substrate with Euler angles (0°, θ, ψ), and a SiO_2 film was formed on the electrodes of Au, so that a boundary acoustic wave device was formed. In this structure, the relationships of θ and ψ of the Euler angles of the $LiNbO_3$ substrate with the acoustic velocities V, the electromechanical coefficients k^2, the propagation losses α, and the temperature coefficients of frequency TCF of the SH type boundary acoustic wave and the Stoneley wave were measured. The results of the SH type boundary acoustic wave are shown in Fig. 12, and the results of the Stoneley wave are shown in Fig. 13.

In the entire regions shown in Figs. 12 and 13, the propagation loss α was 0 dB/λ. In addition, the velocity V and the temperature coefficient of frequency TCF were not significantly changed at ϕ of 0° shown in Figs. 9 and 11. Hence, in Figs. 12 and 13, the results of the electromechanical coefficient k^2 (%) are only shown.

As apparent from Fig. 13, the electromechanical coefficient k^2, which is a response of the Stoneley wave, is small, such as 1.5% or less, in the region surrounded by points A01 to A13 shown in the following Table 2. In addition, the electromechanical coefficient k^2 in the region surrounded by points B01 to B12 shown in the following Table 3 is 1.0% or less, and that in the region surrounded by points C01 to C08 shown in the following Table 4 is superior, such as 0.5% or less. In addition, the electromechanical coefficient, which is a response of the Stoneley wave, at Euler angles (0°, 106°, 0°) was approximately 0%.

[Table 2]

Points	ψ (°)	θ (°)
A01	0	116
A02	11	118
A03	20	123
A04	25	127
A05	33	140
A06	60	140
A07	65	132
A08	54	112
A09	48	90
A10	43	87
A11	24	90
A12	0	91
A13	0	116

[Table 3]

Points	ψ (°)	θ (°)
B01	0	114
B02	11	115
B03	24	120
B04	37	132
B05	42	137
B06	48	137
B07	52	135
B08	55	129
B09	46	99
B10	40	93
B11	0	94
B12	0	114

[Table 4]

Points	ψ (°)	θ (°)
C01	0	112
C02	11	112
C03	36	116
C04	40	110
C05	36	103
C06	20	99
C07	0	98
C08	0	112

Next, as apparent from Fig. 12, the electromechanical coefficient k^2 of the SH type boundary acoustic wave is large, such as 2% or more, in the region surrounded by points F01 to F06 shown in the following Table 7 and is 5% or more in the region surrounded by points E01 to E07 shown in the following Table 6. In addition, the electromechanical coefficient k^2 is preferably large, such as 10% or more, in the region surrounded by points D1 to D07 shown in the following Table 5 and becomes maximum at Euler angles (0°, 97°, 0°).

[Table 5]

Points	ψ (°)	θ (°)
D01	0	126
D02	13	123
D03	25	112
D04	30	96
D05	29	80
D06	0	80
D07	0	126

[Table 6]

Points	ψ (°)	θ (°)
E01	0	133
E02	16	129
E03	27	120
E04	37	98
E05	38	80
E06	0	80
E07	0	133

[Table 7]

Points	ψ (°)	θ (°)
F01	20	140
F02	34	125
F03	44	106
F04	55	80
F05	0	80
F06	20	140

In addition, under conditions shown in Tables 2 to 7, it is confirmed that even when Ag, Cu, Al, Fe, Ni, W, Ta, Pt, Mo, Cr, Ti, ZnO, or ITO is used as the electrode material instead of Au, superior properties equivalent to those described above can also be obtained.

In addition, also in Figs. 12 and 13 and Tables 2 to 7, when $-\psi$ is used instead of ψ, and when $\theta+180°C$ is used instead of θ, for example, a plus or a minus sign of the power flow angle is merely reversed, and it is confirmed that superior results equivalent to each other can be obtained.

[Experimental Example 3]

Next, electrodes of Au having a thickness of 0.06 λ were formed on respective $LiNbO_3$ substrates with Euler angles (ϕ,

105°, 0°) and Euler angles (0°, 105°, ψ), and SiO_2 films were formed to cover the electrodes of Au, so that boundary acoustic wave devices were formed. In this case, the relationships of the Euler angles θ and ψ of the $LiNbO_3$ substrates with the acoustic velocities V, the electromechanical coefficients k^2, the propagation losses α, the temperature coefficients of frequency TCF, and the power flow angles (PFA) of an SH type boundary acoustic wave (U2) and a Stoneley wave (U3) were measured. Figs. 14 to 17 show the results obtained when the $LiNbO_3$ with Euler angles (ϕ, 105°, 0°) was used, and Figs. 18 to 21 show the results obtained when the $LiNbO_3$ with Euler angles (0°, 105°, ψ) was used. In the entire region of ϕ of 0° to 90°, the propagation loss α is 0 dB/λ.

As apparent from Fig. 16, the electromechanical coefficient k^2 of the Stoneley wave is small, such as 1.5% or less, in the range of ϕ of 0° to 31°; the electromechanical coefficient k^2 of the Stoneley wave is further decreased to 1.0% or less in the range of ϕ of 0° to 26°; the electromechanical coefficient k^2 of the Stoneley wave is decreased to 0.5% or less in the range of ϕ of 0° to 19°; and the electromechanical coefficient k^2 of the Stoneley wave becomes approximately 0% at ϕ of 0°, so that it is understood that a spurious response caused by the Stoneley wave is decreased. In addition, in the range of ϕ of 0° to 90°, the TCF of the SH type boundary acoustic wave is preferably in the range of -37 to -35 ppm/°C.

In both cases in which the Euler angles are (ϕ, 105°, 0°)

and Euler angles are ($-\phi$, 105°, 0°), it is confirmed that results equivalent to each other can be obtained.

In addition, as apparent from Fig. 20, the electromechanical coefficient k^2 of the Stoneley wave is small, such as 1.5% or less, in the range of ψ of 0° to 53°; the electromechanical coefficient k^2 of the Stoneley wave is decreased to 1.0% or less in the range of ψ of 0° to 47°; and the electromechanical coefficient k^2 of the Stoneley wave in the range of ψ of 0° to 38° is further decreased to 0.5% or less. At ψ of 0°, the electromechanical coefficient of the Stoneley wave is decreased to approximately 0%, and it is understood that a spurious response caused by the Stoneley wave is decreased. In addition, in the range of ψ of 0° to 90°, the TCF of the SH type boundary acoustic wave is preferably in the range of -35 to -31 ppm/°C.

It is confirmed that in both cases in which the Euler angles are (0°, 105°, ψ) and (0°, 105°, $-\psi$), for example, a plus or a minus sign of the power flow angle is merely reversed, and properties equivalent to each other can be obtained.

[Experimental Example 4]

Incidentally, in general, it has been known that the pass band width of a longitudinally coupled resonator filter in which a plurality of IDTs is disposed between reflectors and the pass band width of a ladder filter or a lattice filter in which resonators are connected to each other are each approximately proportional to the electromechanical coefficient k^2. In

addition, it has also been known that the band width of a resonator, that is, the difference between a resonant frequency and an antiresonant frequency is approximately proportional to the electromechanical coefficient k^2. Hence, in the case in which an SH type boundary acoustic wave is used, when the electromechanical coefficient k^2 of a Stoneley wave is small, and when the electromechanical coefficient k^2 of the SH type boundary acoustic wave can be changed under the conditions in which a spurious response caused by the Stoneley wave is small, it is understood that the band width can be easily adjusted. That is, the degree of freedom for designing a filter and a resonator can be increased.

As shown in Fig. 20, when ψ of the Euler angle is changed from 0° to 60°, the electromechanical coefficient k^2 of the SH type boundary acoustic wave is changed from 16.4% to 0.1%. In the above region, the electromechanical coefficient k^2 of the Stoneley wave is small. Furthermore, ϕ and θ of the Euler angles are angles determining a cut surface of a substrate which propagates a boundary acoustic wave, and ψ of the Euler angle is an angle determining the propagation direction of the boundary acoustic wave. Hence, as shown in Fig. 1(a), when the first and the second boundary acoustic wave elements are disposed on the substrate having the same cut surface so that the propagation directions X1 and X2 are different from each other, the conditions can be obtained in which the electromechanical coefficients k^2 are different from each other.

That is, in the boundary acoustic wave device 1 shown in Fig. 1, although the first and the second boundary acoustic wave elements 2 and 3 are formed from the single crystal substrate 4 made of the same piezoelectric crystal, since the propagation directions X1 and X2 of the boundary acoustic wave are different from each other, the electromechanical coefficients k^2 are made different from each other. Hence, a single crystal substrate having a different cut surface is not necessarily prepared in accordance with a required band width, and various band widths can be realized using the same single crystal substrate. The Euler angles of the single crystal substrate 4 are not limited to Euler angles (0°, 105°, ψ), and ϕ and θ of the Euler angles may be changed. The Euler angles described in Experimental Examples 2 and 3 are preferably used since the electromechanical coefficient k^2 of the SH type boundary acoustic wave can be sufficiently increased, and the electromechanical coefficient k^2 of the Stoneley wave which causes a spurious signal can be decreased.

[Experimental Example 5]

A NiCr film having a thickness of 0.001 λ was formed as an adhesion layer on a single crystal substrate of a $LiNbO_3$ substrate with Euler angles (ϕ, 105°, 0°) by a deposition method. Subsequently, after a film was formed from Au by deposition on the NiCr film, an electrode structure shown in Fig. 22 was formed by a photolithographic lift-off method.

In this electrode structure, there are provided

interdigital electrodes 31 and reflectors 32 and 33 disposed at two sides of the interdigital electrodes 31 along the propagation direction of a boundary acoustic wave.

The interdigital electrodes 31 and the reflectors 32 and 33 were disposed to incline the directions of electrode fingers thereof, so that a propagation direction β of the boundary acoustic wave was changed in the range of -50 to 50°.

In addition, a SiO_2 film having a thickness of λ was formed by RF magnetron sputtering so as to cover the interdigital electrodes 31 and the reflectors 32 and 33. The temperature for film formation was set to 250°C.

In the interdigital electrodes 31, the number of pairs of electrode fingers was set to 50.5, and weighting of intersection-width was performed as shown in the figure so as to suppress transverse mode spuriousness. In addition, the number of electrode fingers of each of the reflectors 32 and 33 was set to 51. In addition, the aperture length was set to 30 λ. In this example, λ was a placement period of strips of the interdigital electrodes 31 and the reflectors 32 and 33 and was set to 3.0 μm.

The duty ratio of the interdigital electrodes 31 and the reflectors 32 and 33 was set to 0.58, the thickness of the Au film was set to 0.05 λ, and the thickness of the SiO_2 film was set to λ.

Impedance-frequency characteristics and phase characteristics of the boundary acoustic wave device formed as

described above are shown in Figs. 23(a) to 23(c) and Figs. 24(a) to 24(c). In Figs. 23(a) to 24(c), the impedance on the vertical axis is a value represented by the following equation (8).

$$
\begin{aligned}
F(\phi, \theta, \psi) &= F(60°-\phi, -\theta, \psi) \\
&= F(60°+\phi, -\theta, 180°-\psi) \\
&= F(\phi, 180°+\theta, 180°-\psi) \\
&= F(\phi, \theta, 180°+\psi) \quad \cdots \quad \text{Equation (8)}
\end{aligned}
$$

In Fig. 23(c) and Figs. 24(a) to 24(c), a spurious signal generated at around 1,100 to 1,130 MHz is a spurious signal caused by the Stoneley wave. When ϕ of the Euler angles is set to 20° or more, a spurious signal caused by the Stoneley wave is slightly generated. However, as shown in Experimental Example 2, when θ of the Euler angles is set to 106°, the spurious signal caused by the Stoneley wave can be effectively suppressed.

In addition, in the characteristics shown in Fig. 23(c) and Figs. 24(a) to 24(c), although a spurious signal caused by the Stoneley wave is generated, the degree thereof is sufficiently small, and as a result, no practical problem occurs.

Figs. 25(a) to 25(c) to Figs. 28(a) to 28(c) are graphs each showing the relationship between ψ of the Euler angles and resonant-antiresonant difference which is obtained by dividing the difference between a resonant frequency and an antiresonant frequency of the above one-port type boundary acoustic wave resonator by the resonant frequency. The Euler angle θ is 90° in Figs. 25(a) to 25(c), θ is 100° in Figs. 26(a) to 26(c), θ is

105° in Figs. 27(a) to 27(c), and θ is 110° in Fig. 28.

In addition, Figs. 29(a) to 29(c) and Figs. 32(a) to 32(c) are graphs showing the relationships between ψ of the Euler angles and the impedance, which are obtained when θ of the Euler angles is 95°, 100°, 105°, and 110°.

In this example, the impedance value is represented by Equation (8) as is the case shown in Figs. 23(a) to 23(c).

As can be seen from Figs. 25 to 32, it is understood that when ψ indicating the propagation direction is changed, the band width can be adjusted.

In Figs. 25(a) to 25(c) to Figs. 32(a) to 32(c), the electrode thickness is set to 0.04 λ to 0.06 λ, the Euler angle θ is set to 95 to 110°, and the duty ratio is set to 0.636.

[Experimental Example 6]

In accordance with the method in Experimental Example 5, 7 one-port type boundary acoustic wave resonators were formed, and as shown in Fig. 33, a ladder filter was formed in which 5 boundary acoustic wave resonators were connected to form a ladder structure. In Fig. 33, a ladder filter 40 has series arm resonators S1 and S2 on a series arm connecting an input terminal and an output terminal. In addition, between the series arm and a reference potential, 3 parallel arm resonators P1 to P3 are provided.

In this experimental example, on the same single crystal substrate, 5 boundary acoustic wave resonators were formed. The single crystal substrate used in this example was a $LiNbO_3$

substrate with Euler angles (0°, 105°, 0° to 140°).

In each one-port type boundary acoustic wave resonator, the number of electrode fingers of each reflector was set to 51. In the parallel arm resonators P1 and P3, the number of pairs of electrode fingers of interdigital electrodes was set to 50.5, and the aperture length was set to 30 λ. The series arm resonators S1 and S2 were formed by connecting 2 resonators in series which were the same as that used for forming the parallel arm resonators P1 and P3. As for the parallel arm resonator P2, the number of pairs of electrode fingers of interdigital electrodes was set to 100.5, and the aperture length was set to 30 λ. As for the parallel arm resonators P1 to P3, the wavelength λ of the interdigital electrodes and the reflectors was set to 3.0 λ. In addition, λ of the series arm resonators S1 and S2 was disposed so that the antiresonant frequency of the parallel arm resonators P1 and P3 and the resonant frequency of the series arm resonators S1 and S2 were approximately overlapped with each other. The duty ratio of the interdigital electrodes and that of the reflectors were both set to 0.58, the electrode thickness of Au was set to 0.05 λ, and the thickness of the SiO_2 film was set to 2.5 λ.

The frequency characteristics of the ladder filter obtained when the Euler angle ψ was changed to 0°, 20°, and 30° are shown in Figs. 34(a) to 35(b).

In Figs. 34 and 35, the horizontal axis indicates a normalized frequency obtained by dividing the frequency by a 3-

dB band width of each filter. The 3-dB center frequency is approximately 1,080 MHz.

As apparent from Figs. 34 and 35, it is understood that when the Euler angle ψ is changed, the band width can be adjusted. In addition, when the normalized frequency is in the range of 1.05 to 1.10, a spurious signal is generated; however, since a spurious signal caused by the Stoneley wave is sufficiently suppressed, no practical problems occur at all. In addition, the minimum insertion loss at ψ of zero was superior, such as 1.27 dB.

Next, electrodes were formed from Cu, and a ladder filter was formed in a manner equivalent to that described above. In this case, the electrode thickness of the interdigital electrodes and that of the reflectors were set to 0.10 λ, and the duty ratio was set to 0.6. As the piezoelectric single crystal substrate, a $LiNbO_3$ substrate with Euler angles (0°, 110°, 0°) was used. In addition, under the electrodes made of Cu, as an adhesion layer, a Ti film having a thickness of 0.003 λ was formed as a sub-electrode layer. Furthermore, on the electrode layer primarily composed of Cu, a third electrode layer made of Al having a thickness of 0.003 λ was formed as a protective layer. The placement period λ of electrode fingers of the IDT and that of the reflector were set to 3 μm. In addition, the thickness of the SiO_2 film was set to 2 λ, and onto the solid layer made of the SiO_2 film, an epoxy resin was applied so as to have a thickness of 5 λ or more, followed by curing. The

frequency characteristics of the ladder filter thus obtained are shown in Fig. 37. In Fig. 37, the minimum insertion loss was superior, such as 1.7 dB.

As apparent from Fig. 37, it is understood that even when the main electrode layer is formed from Cu, superior filter characteristics can be obtained.

The method described above which adjusts the band width by changing the electromechanical coefficient k^2 using the propagation direction of a boundary acoustic wave may be applied to a lattice filter formed by disposing a plurality of one-port type resonators, a longitudinally coupled resonator type filter formed by disposing a plurality of IDTs, a two-port type resonator, and a laterally coupled filter in addition to the above one-port type resonator and the ladder filter using a plurality of one-port type resonators.

[Experimental Example 7]

After electrodes made of Au having a thickness of 0.5 λ were formed on a $LiNbO_3$ substrate with Euler angles (0°, θ, 0°), polycrystalline Si having an infinite thickness was formed as the solid layer on the above electrodes made of Au in one case, and SiO_2 having a thickness of 0.1 λ and polycrystalline Si having an infinite thickness were formed as the solid layer on the above electrodes made of Au in the other case. Subsequently, the relationships of the Euler angle θ with the acoustic velocities V, electromechanical coefficients k^2, propagation losses α, and temperature coefficients of frequency

TCF (PFA) of an SH type boundary acoustic wave (U2) and a Stoneley wave (U3) were measured. Figs. 38(a) to 38(c) show the results obtained when the polycrystalline Si having an infinite thickness was formed, and Figs. 39(a) to 39(b) show the results obtained when the SiO_2 having a thickness of 0.1 λ and the polycrystalline Si having an infinite thickness were formed.

In the entire region of θ from 0° to 180°, the propagation loss α was 0 dB/λ and the power flow angle PFA was 0°.

As apparent from the comparison between the results shown in Figs. 38(a) to 38(c) and those shown in Figs. 39(a) to 39(c), it is understood that compared to the case in which the SiO_2 solid layer is used, when the polycrystalline Si is used, although the electromechanical coefficient k^2 of the Stoneley wave cannot be decreased to zero in the case in which the SH type boundary acoustic wave is used, the electromechanical coefficient of the Stoneley wave tends to decrease at an Euler angle θ of 106° to 115°. Hence, it is understood that even in the case in which the solid layer is formed from polycrystalline Si, a spurious signal caused by the Stoneley wave can be suppressed at the same Euler angle as that in the case in which the solid layer is formed from SiO_2.

[Experimental Example 8]

An RF module for mobile phones has a transmitting block and a receiving block, and a transmitting band and a receiving band are different from each other. In an Rx filter used in the receiving block, the receiving band is a pass band, and the

transmitting band is a stop band. In addition, in a Tx filter used in the transmitting block, the transmitting band is a pass band, and the receiving band is a stop band.

Accordingly, in the RF filter used for mobile phones, it may be strongly required in some cases that with respect to the pass band, the amount of attenuation in the stop band, which is at one side of the pass band, is sufficiently large. In this case, it has been known that asymmetric pass characteristics of the filter have to be intentionally formed so that the amount of attenuation in the receiving band is sufficiently increased in the case of the Tx filter and so that on the other hand, the amount of attenuation in the transmitting band is sufficiently increased in the case of the RF filter.

In order to form the asymmetric pass characteristics of a filter, a coil or a capacitor may be connected to the filter. For example, in the case of a ladder filter, when a coli is connected to one of a parallel arm resonator and a series arm resonator so as to increase the difference between the resonant and the antiresonant frequencies of the above one resonator, the pass band can be made asymmetric. However, since a coil or a capacitor must be connected to the filter, the number of parts is increased, and in addition, the exterior dimension of the filter is inevitably increased.

On the other hand, in the present invention, when a resonator is used in which the band is preferably adjusted by changing the propagation direction ψ as described in

Experimental Example 5, the above problem can be solved. In Fig. 36, the pass band of a ladder filter is shown which was formed in a manner equivalent to that for the ladder filter shown in Fig. 33 except that the propagation directions of the parallel arm resonators P1 and P3 were set so that $\psi=20°$ was satisfied, and the propagation directions of the series arm resonators S1 and S2 were set so that $\psi=0°$ was satisfied.

As apparent from Fig. 36, it is understood that at a low frequency side of the pass band, the attenuation rapidly occurs, and that at a normalized frequency of 0.956, although the amount of attenuation was merely 34 dB according to the pass characteristics of the ladder filter shown in Figs. 34 and 35, the amount of attenuation is large, such as 44 dB, according to the characteristics shown in Fig. 36.

In addition, when the propagation directions of the parallel arm resonators P1 and P3 and the propagation directions of the series arm resonators S1 and S2 are reversed therebetween, the amount of attenuation at a broadband side of the pass band can be improved.

The Euler angles of the $LiNbO_3$ substrate which can adjust the electromechanical coefficient k^2 by the propagation direction are present, for example, at around (90°, 90°, 0°) in addition to Euler angles (0°, 105°, 0°) shown in Experimental Example 5. Hence, in a $SiO_2/Au/LiNbO_3$ structure, when the thickness of Au is set to 0.07 λ, and when the Euler angles of the $LiNbO_3$ substrate is changed from (90°, 90°, 0°) to (90°, 90°, 60°), the

electromechanical coefficient can be adjusted from 16.8% to 0.8%.

A method for improving performance of a boundary acoustic wave device using the structure in which the band width is adjusted by changing the electromechanical coefficient k^2 using the propagation direction may be applied to various structures besides the above ladder filter in which the steepness in the vicinity of the pass band is increased. For example, as shown in Fig. 40, the above method may be applied to a two-input and two-output filter chip having two bands in which an Rx filter 41 and a Tx filter 42 are provided to form one chip. In this case, the pass band of the Rx filter 41 and that of the Tx filter 42 are, for example, as shown in Fig. 41. In Fig. 41, a method equivalent to that described above may be performed, that is, for example, the steepness at a low frequency side of the pass band of the Rx filter may be increased, or the steepness at a high frequency side of the pass band of the Tx filter may be increased. In addition, as shown in Fig. 42, the above method may also be applied to a one-input and two-output filter having two bands in a manner equivalent to that described above. In the filter shown in Fig. 42, input of the Rx filter and that of the Tx filter are connected to each other.

In addition, in the structure in which boundary acoustic wave filters are connected to each other in series or in parallel, when a high frequency side or a low frequency side of the pass band of one boundary acoustic wave filter and a high

frequency side or a high frequency side of the pass band of another boundary acoustic wave filter are designed so as to be in contact with each other, a filter having a broad band can be formed. In this case, it is preferable that ends of the pass bands be in contact with each other at which the amount of attenuation is 3 dB. In the configuration thus designed, when boundary acoustic wave filters having different propagation directions are used in accordance with the present invention so that one boundary acoustic wave filter is used for a broad band and another boundary acoustic wave filter is used for a narrow band, the steepness can be increased at one of the high frequency side and the low frequency side of the pass band. That is, in the structure in which a first boundary acoustic wave filter 45 and a second boundary acoustic wave filter 46 are connected to each other in parallel as shown in Fig. 43, or in the structure in which a first boundary acoustic wave filter 47 and a second boundary acoustic wave filter 48 are connected to each other in series as shown in Fig. 45, when the pass band of the first boundary acoustic wave filter and that of the second boundary acoustic wave filter are set so as to be very close to each other, synthesized band characteristics indicated by a thick solid line can be obtained as shown in Fig. 44. Even in the structure as described above, when the propagation direction is adjusted in accordance with the present invention, broadband filter characteristics can be easily designed.

Furthermore, also in the structure in which a trap is

formed for pass band characteristics by connecting a one-port type resonator in series or in parallel to one of an input terminal, a connection terminal, or an auxiliary connection terminal of a longitudinally coupled filter, when the propagation direction of the longitudinally coupled filter and that of the resonator are made different from each other, a trap band can be changed.

Furthermore, in a method for designing various boundary acoustic wave devices, when the technique is used in which the band width is adjusted by changing the electromechanical coefficient k^2 using the propagation direction, designing and manufacturing of boundary acoustic wave devices can be simplified. In addition, miniaturization can be advantageously achieved by one-chip integration.

By the boundary acoustic wave device according to the present invention, a longitudinally coupled filter may be formed. Fig. 46 is a schematic plan view only showing an electrode structure obtained when a longitudinally coupled filter is formed.

In Fig. 46, the electrode structure of a longitudinally coupled filter 51 is only shown by a schematic plan view. In practice, the electrode structure shown in Fig. 46 is formed at a boundary between a first vise layer and a second vise layer. That is, the front cross-sectional view of the longitudinally coupled filter 51 is approximately equivalent to that of the boundary acoustic wave device 1 shown in Fig. 1(b), and the

electrode structure is only modified as shown in Fig. 46.

As shown in Fig. 46, in the longitudinally coupled filter 51, three IDTs 52 to 54 are disposed along the propagation direction of a boundary acoustic wave. Reflectors 55 and 56 are disposed at two sides of a region in which the IDTs 52 to 54 are provided along the propagation direction of the boundary acoustic wave. The center IDT 53 is connected to input terminals, and ends of the IDT 52 and respective ends of the IDT 54 are connected to each other and are then connected to output terminals. That is, the longitudinally coupled filter 51 is a three-IDT type longitudinally coupled boundary acoustic wave filter.

As described above, the electrode structure including the IDTs 52 to 54 and the reflectors 55 and 56 is formed at the boundary between the single crystal substrate and the solid layer.

As the above single crystal substrate, a 105° Y-cut 0° X-propagation $LiNbO_3$ substrate with Euler angles (0°, 105°, 0°) was used to form the longitudinally coupled filter 51 having the following specifications, and the frequency characteristics were measured. The results are shown in Fig. 47.

Electrode structure: after a NiCr film having a thickness of 0.03 λ, a Au film having a thickness of 0.05 λ, and a NiCr film having a thickness of 0.003 λ were laminated to each other in that order, the IDTs 52 to 54 and the reflectors 55 and 56 were formed from this laminated film. In addition, the solid

layer covering the electrodes was formed from a SiO_2 film having a thickness of 2.0 λ.

The number of pairs of the electrode fingers of the IDTs 52 and 54 was set to 6, and the number of pairs of the electrode fingers of the IDT 53 was set to 10. The number of pairs of the electrode fingers of the reflectors 55 and 56 were each set to 40.

The period λ of the IDTs 52 to 54 was set to 3.0 μm, and the period of the reflectors 55 and 56 was set to 3.1 μm.

Next, a longitudinally coupled filter was formed in a manner equivalent to that described above except that the propagation angle of the single crystal substrate was changed by using a 105° Y-cut 20° X-propagation $LiNbO_3$ substrate with Euler angles (0°, 105°, 20°), and subsequently, the frequency characteristics were measured. The results are shown in Fig. 48.

As apparent by comparison between the results shown in Figs. 47 and 48, it is understood that the pass band width is changed by changing the propagation angle. Hence, when a plurality of longitudinally coupled filters having different propagation angles is formed on the same substrate, a plurality of longitudinally coupled filters can be formed having different filter properties such as the pass band widths.

In addition, in the specification of the present invention, as the Euler angles (ϕ, θ, ψ) representing the cut surface of a substrate and the propagation direction of a boundary acoustic

wave, the right-hand Euler angle system is used which has been disclosed in "Acoustic Wave Device Technology Handbook" (edited by Acoustic Wave Device Technology 150th Committee of the Japan Society for the Promotion of Science, first print/first edition issued on Nov. 30, 2001, p. 549). That is, with respect to crystal axes X, Y, and Z of LN, an Xa axis is obtained by ϕ rotation of the X axis about the Z axis in an anticlockwise direction. Next, a Z' axis is obtained by θ rotation of the Z axis about the Xa axis in an anticlockwise direction. A plane including the Xa axis and having the Z' axis as the normal line is set as the cut surface of a substrate. In addition, the direction of an X' axis obtained by ψ rotation of the Xa axis about the Z' axis in an anticlockwise direction is set as the propagation direction of a boundary acoustic wave.

In addition, as for the crystal axes X, Y, and Z of $LiNbO_3$ represented as the initial values of Euler angles, the Z axis is set parallel to the c-axis, the X axis is set parallel to any one of the three equivalent a-axes in three different directions, and the Y axis is set parallel to the normal line of a plane including the X axis and the Z axis.

In addition, Euler angles equivalent to the Euler angles (ϕ, θ, ψ) of $LiNbO_3$ of the present invention in terms of crystallography may be used. For example, according to technical document 7 (Journal of the Acoustical Society of Japan, Vol. 36, No. 3, 1980, pp. 140 to 145), since $LiNbO_3$ is a crystal belonging to the trigonal 3 m point group, the following

equation (A) is satisfied.

$$
\begin{aligned}
F(\phi, \theta, \psi) &= F(60°-\phi, -\theta, \psi) \\
&= F(60°+\phi, -\theta, 180°-\psi) \\
&= F(\phi, 180°+\theta, 180°-\psi) \\
&= F(\phi, \theta, 180°+\psi) \cdots \text{Equation (A)}
\end{aligned}
$$

In the above equation, F is an optional boundary acoustic-wave property such as the electromechanical coefficient k^2, propagation loss, TCF, PFA, or a natural unidirectional property. As for PFA and natural unidirectional property, for example, when the propagation direction is reversed, although a plus or a minus sign indicating the direction is changed, the absolute value of the property is not changed, and hence it can be construed that they are practically equivalent to each other. In addition, although the technical document 7 relates to the surface acoustic wave, even when the boundary acoustic wave is discussed, the symmetry of crystal may also be handled in the same manner as disclosed in the technical document 7. For example, propagation properties of a boundary acoustic wave at Euler angles (30°, θ, ψ) are equivalent to those at Euler angles (90°, 180°-θ, 180°-ψ). In addition, for example, propagation properties of a boundary acoustic wave at Euler angles (30°, 90°, 45°) are equivalent to those at Euler angles shown in Table 8 below.

In addition, the material constant of the electrode used for calculation in the present invention is the value of a

polycrystalline substance; however, even in a crystal substance such as an epitaxial film, since the crystal orientation dependence of a substrate dominantly influences the boundary acoustic wave properties as compared to that of the film itself, also in the case of the equivalent Euler angles represented by the equation (A), equivalent boundary acoustic-wave propagation properties which may not cause any practical problems can be obtained.

[Table 8]

ϕ (°)	θ (°)	ψ (°)
30	90	225
30	270	135
30	270	315
90	90	135
90	90	315
90	270	45
90	270	225
150	90	45
150	90	225
150	270	135
150	270	315
210	90	135
210	90	315
210	270	45
210	270	225
270	90	45
270	90	225
270	270	135
270	270	315
330	90	135
330	90	315
330	270	45
330	270	225